Searches for SUSY

Wolfgang Adam
Institute of High Energy Physics, Austrian Academy of Sciences

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ÖAW

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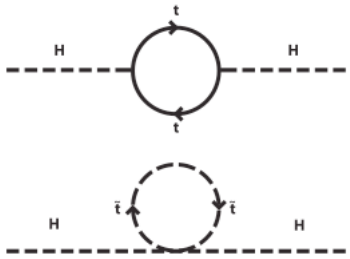
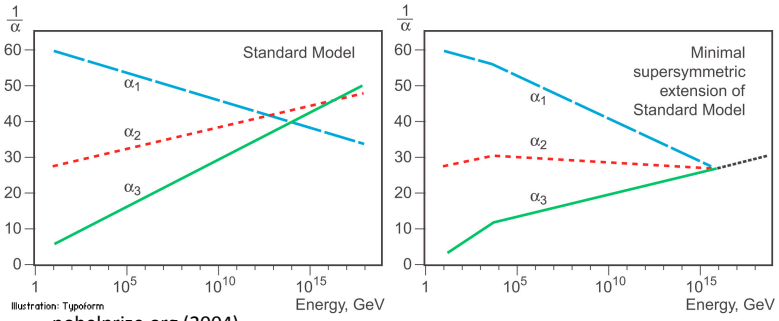
Why look for SUSY after LHC Run1?

The main motivations remain

Hierarchy problem

- low-mass top squarks cancel SM contributions to m(H)
  (+ light higgsinos, gluinos)





nobelprize.org (2004)

Unification of gauge couplings

- Presence of sparticles changes running of couplings

Dark matter

- lightest SUSY particle can be massive, stable, and weakly interacting

With increasingly higher limits, in particular on top squarks, natural SUSY is under pressure …

NASA / Chandra

Outline

- Introduction

- Searches for SUSY production (strong)
- Searches for SUSY production (electroweak)
- R-parity violating and gauge-mediated SUSY breaking scenarios
- A short look back

- Summary

Limited time imposes a selection

Focus on most recent (2016) LHC results

(neglecting indirect limits / precision measurements)

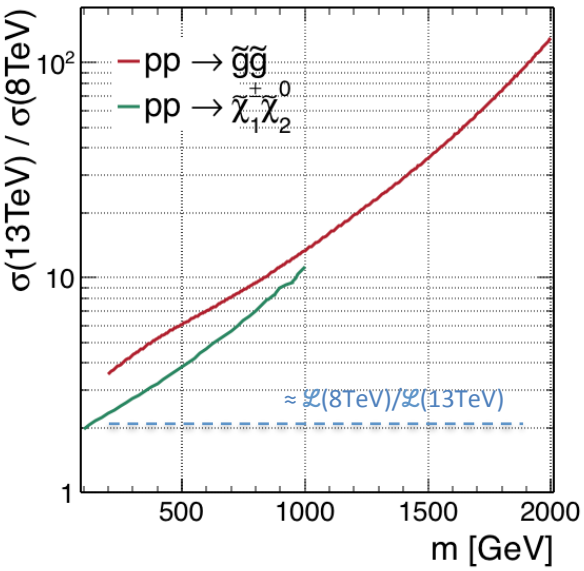
Restrict to subset of models

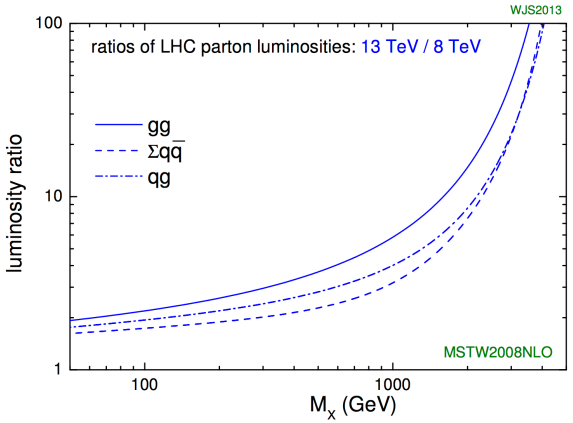
(no long-lived particle searches, no generic dark-matter interpretations)

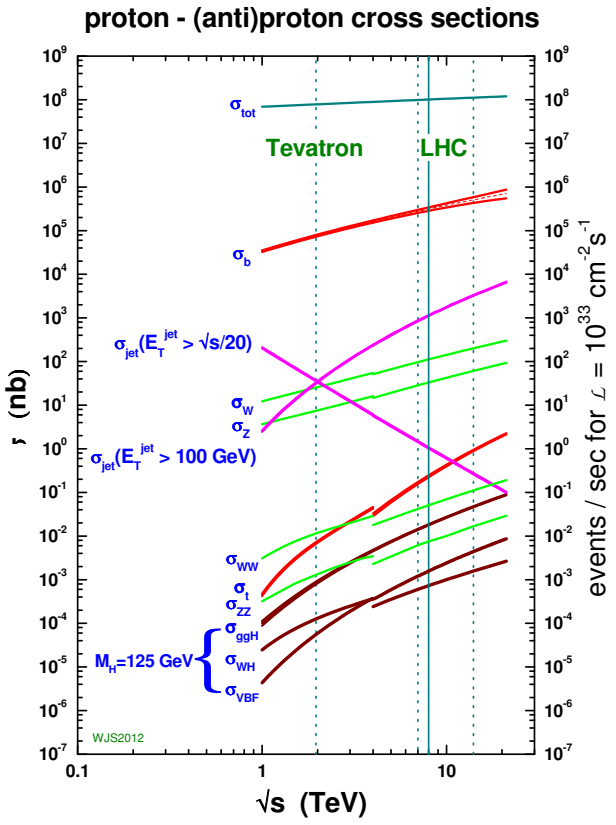
SUSY in 13 TeV pp collisions

Considerably higher cross sections w.r.t. Run1

- in particular for gluon-gluon
- most important gain for the highest masses
  - for many SUSY searches higher than for dominant SM backgrounds (W, tt)





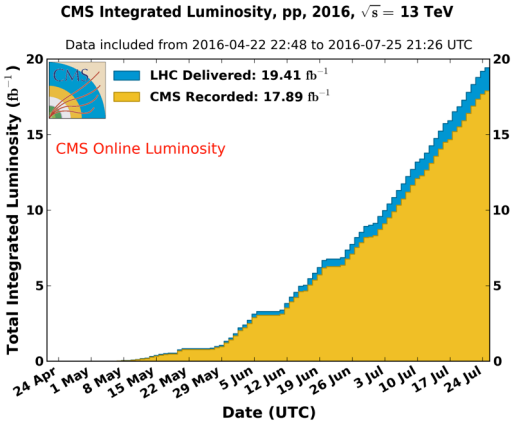


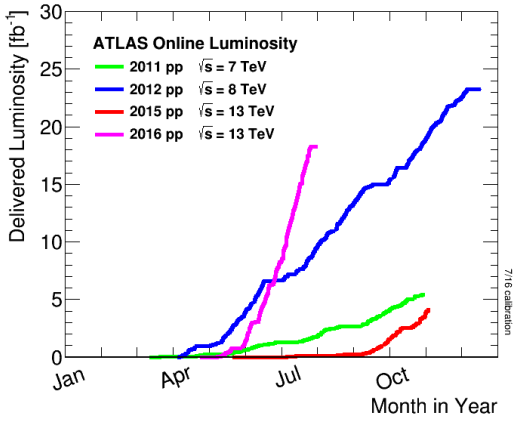
W.J.Stirling

SUSY in 13 TeV pp collisions

Extraordinary LHC performance in 2016

- exceeded design value inst. luminosity
- $\int \mathcal{L}$ (2016) already >> $\int \mathcal{L}$ (2015) !





Experimental challenges

- need to keep trigger rates under control at increasing luminosity
- deal with increasing number of simultaneous collisions
- follow data-taking conditions with on- and offline calibrations
  (particularly important for SUSY measurements –
  high object multiplicities, select tails of distributions)

Which SUSY flavor ?

Potential parameter space is enormous

cMSSM : 4 + 1; pMSSM : 19; MSSM : ~ 105; NMSSM, …

Concentrate on 3 scenarios

R-parity conserving (lightest SUSY particle = $\tilde{\chi}_1^0$)

- provides DM candidate
- "classical" SUSY signatures with high missing E_T (MET)
- strong or electroweak production

R-parity violating, different LSPs

- couplings strongly constrained (proton stability)
- loose MET handle for bkg reduction
- alternative signatures like high jet multiplicity

Gauge mediated SUSY breaking

- decay chains terminate with (low-mass, invisible)
- typical signature: MET + $\tilde{G}$ photons or Zs from last decay step

The SUSY hunter's toolbox

Standard objects
- isolated light, tau leptons
- jets, b-tagged jets
- missing energy (energy sum or from jets)

Kinematic variables
- m_T (lepton/MET, b/MET)
- m_{T2} (stransverse mass)
- m_{CT} (contransverse mass)

common feature: endpoint at m(parent)

Hadronic / total energy
- H_T (scalar sum of (jet) p_Ts)
- m_{eff} (sum of jet & lepton p_Ts, MET)
- E_T^{sum} (sum of all particle p_Ts)

Composite (boosted) objects
- topness
- boosted W and top taggers
- jet substructure

Event kinematics
- hemispheres
- razor / super-razor
- recursive jigsaw reconstruction

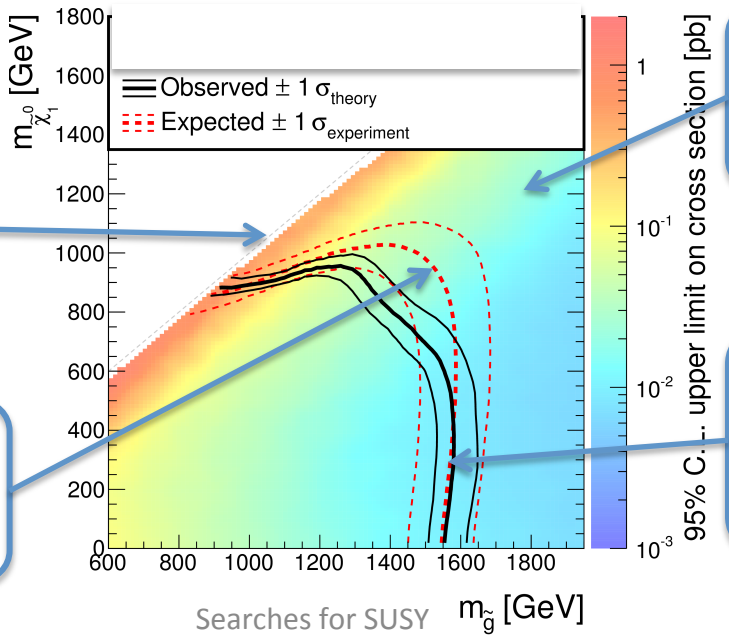
Simplified model spectra

THE interpretation tool for SUSY searches @ LHC

Pros
- closely related to exp. observables
  - understand features
- limited number of parameters
  - results as 2D scans
- "easy" reinterpretation (cross-section limit)

Cons
- no complete model
  - consistency, higher-order corrections?
- application to other (full) models
  - ignores details of production, spin structure, …

A short interpretation guide



Kinematic limit

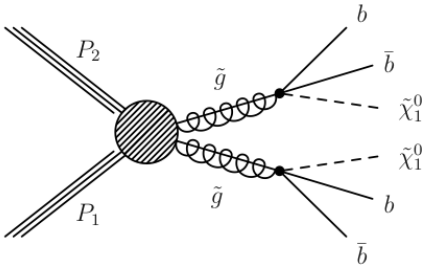
Map of observed cross section limits
- under assumption BR=1

Expected (median) mass limit
- at nominal production cross section
- 1σ variations due to stat+syst

Observed mass limit
- variations correspond to ±1σ uncertainty on the total production cross section

GLUINO PAIR PRODUCTION

Gluino decays to bb+LSP



Gluinos: highest SUSY production cross section

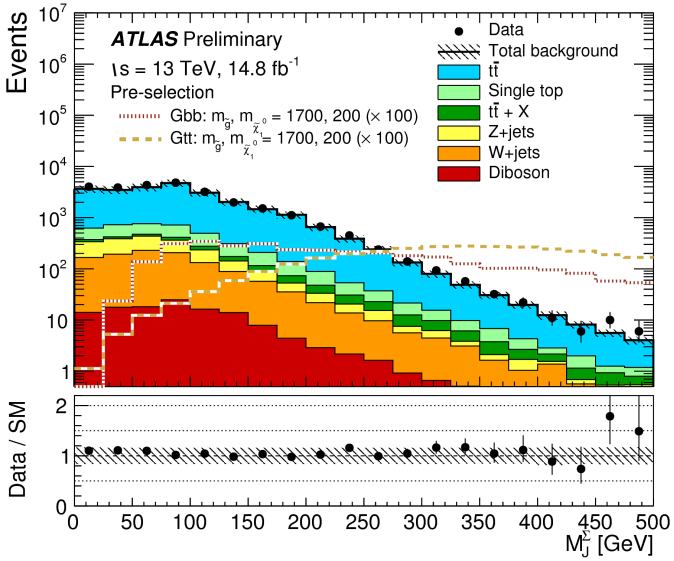
- can give access to other sparticles via decay chains
- here: consider decays to two quarks and the LSP

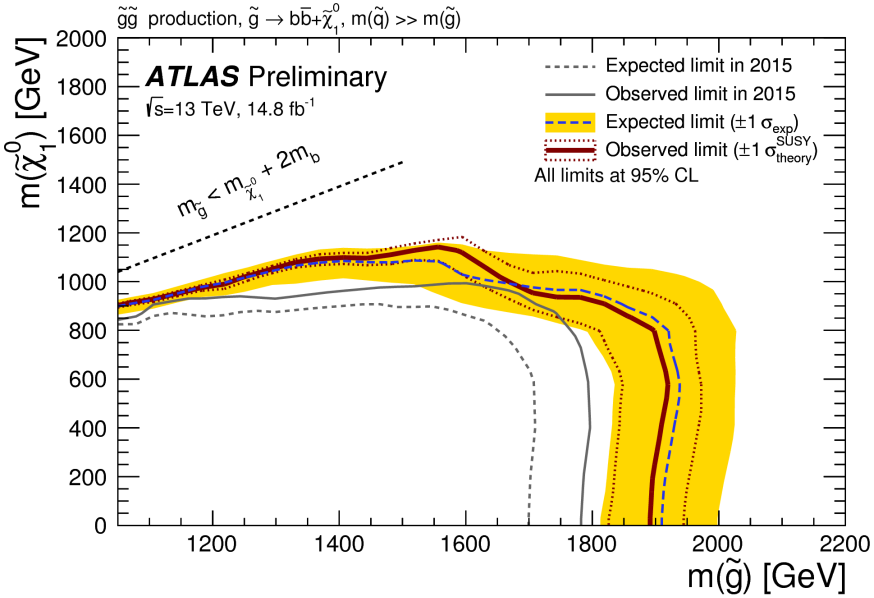
Hadronic search with b-jets

ATLAS-CONF-2016-052

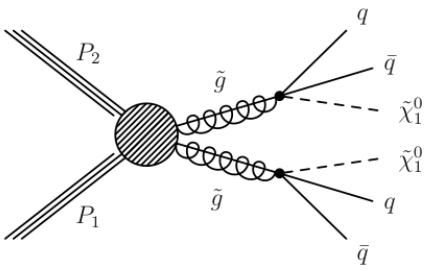
- ≥4 jets, ≥3 b, no lepton (this model)
- key variables: #b-jets, MET, m_{eff}, m_T, large-radius jet masses

Other results
- CMS-SUS-16-014
- CMS-SUS-16-015
- CMS-SUS-16-016





Gluino decays to qq+LSP



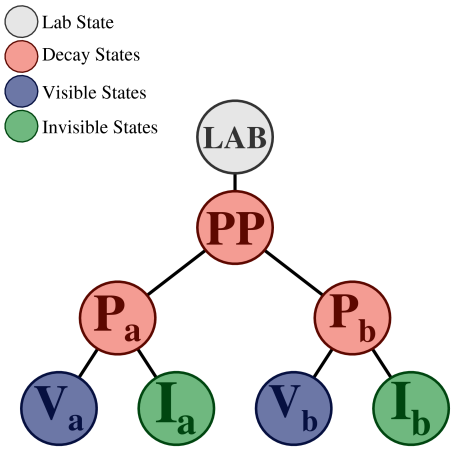
Hadronic search

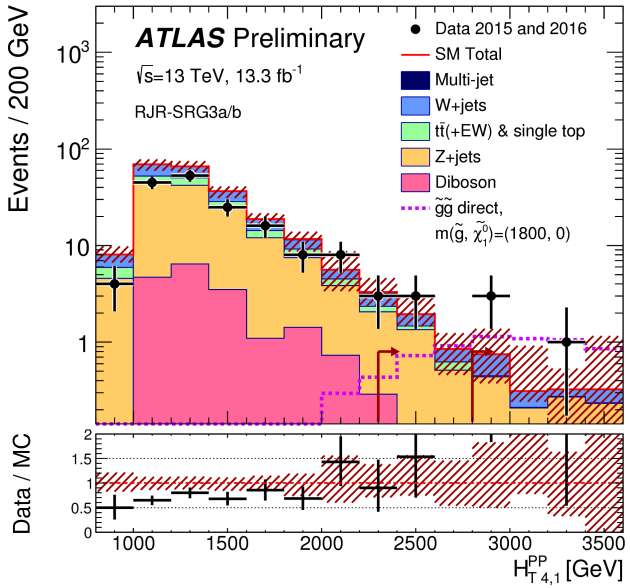
ATLAS-CONF-2016-078

- two search strategies: m_{eff} and RJR-based

Recursive jigsaw reconstruction

- based on assumption of decay tree
- fix set of rules to resolve combinatorics and unknowns in invisible system
- can form set of variables in the rest frame of each level in the decay tree

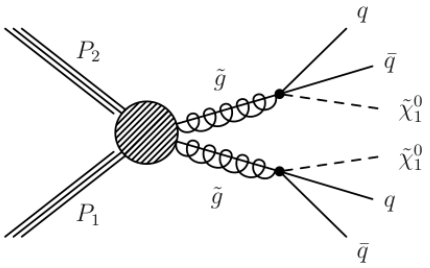




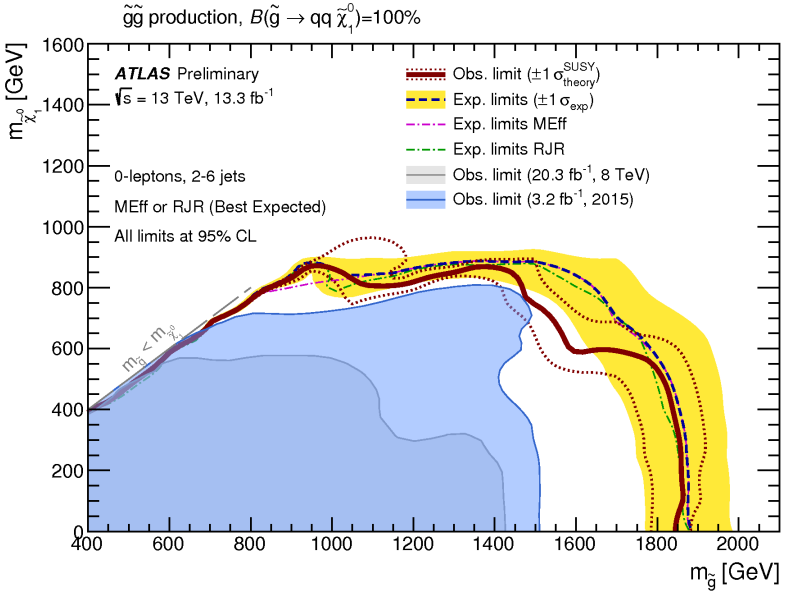
can be scale-sensitive:
scalar sums of momenta
or without unit:
ratios of sums; angles

Other results
- CMS-SUS-16-014
- CMS-SUS-16-015

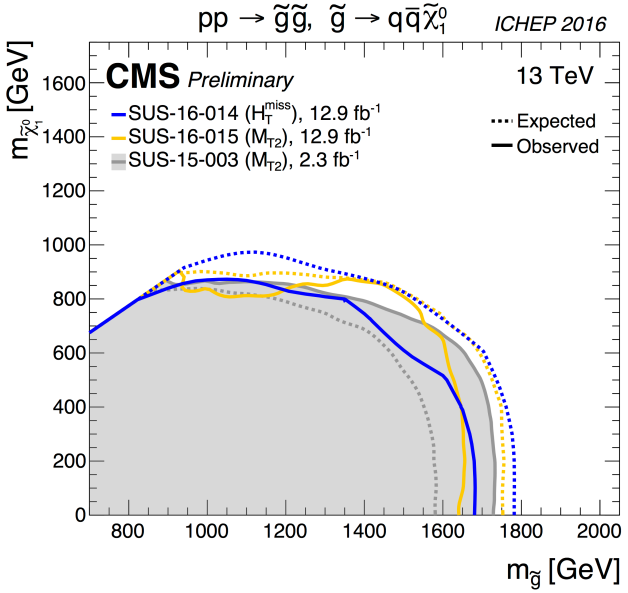
Gluino decays to qq+LSP



Summary of decays to light quarks + LSP

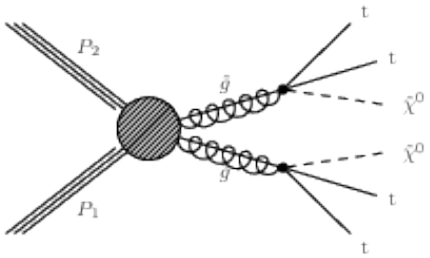


ATLAS-CONF-2016-078



CMS-SUS-16-014
CMS-SUS-16-015

Gluino decays to tt+LSP



Hadronic search

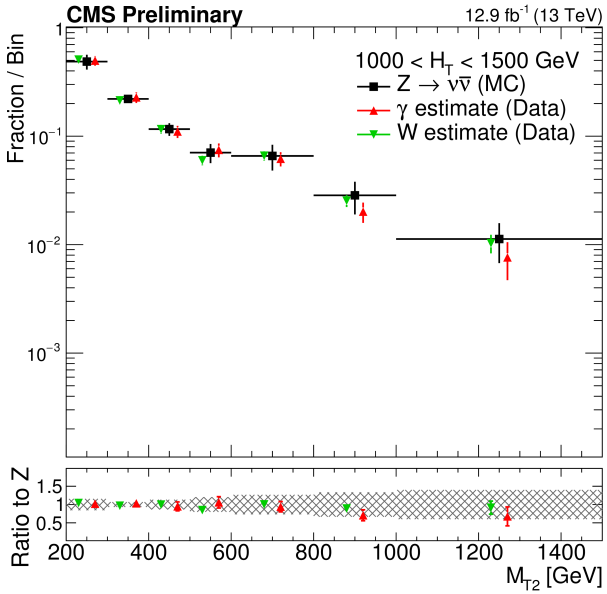
CMS-SUS-16-015

- key variable: M_{T2}
- also binned in #jets, #b-jets, H_T

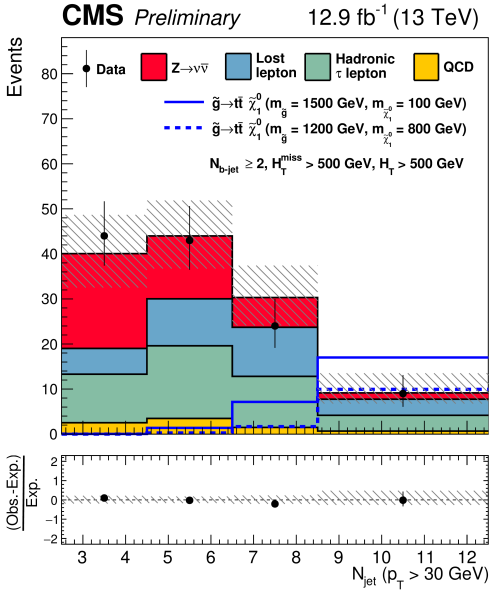
Hadronic search

CMS-SUS-16-016

- key variable: missing H_T
- also binned in #jets, #b-jets, H_T

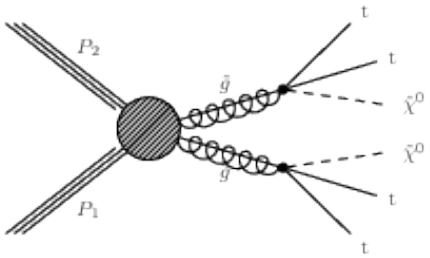


Example of background estimation: irreducible contribution from Z(→νν)+jets

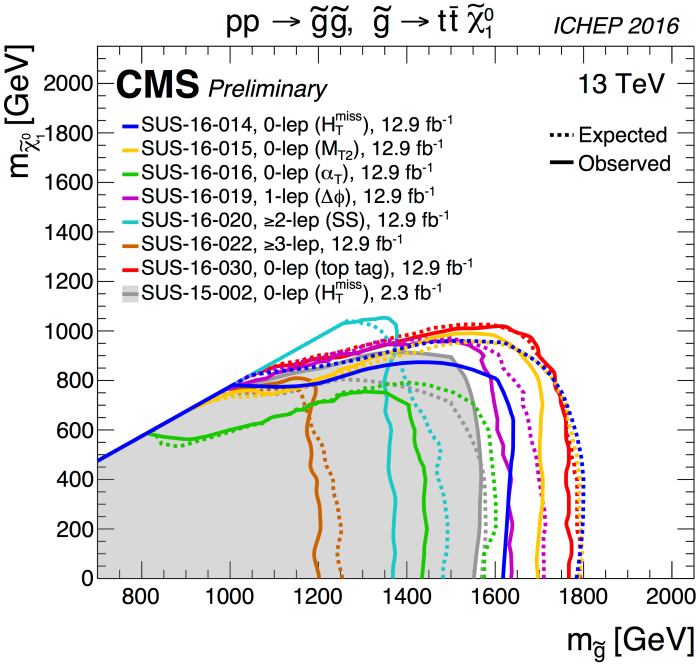


Jet multiplicity for a signal-enriched region

Gluino decays to tt+LSP

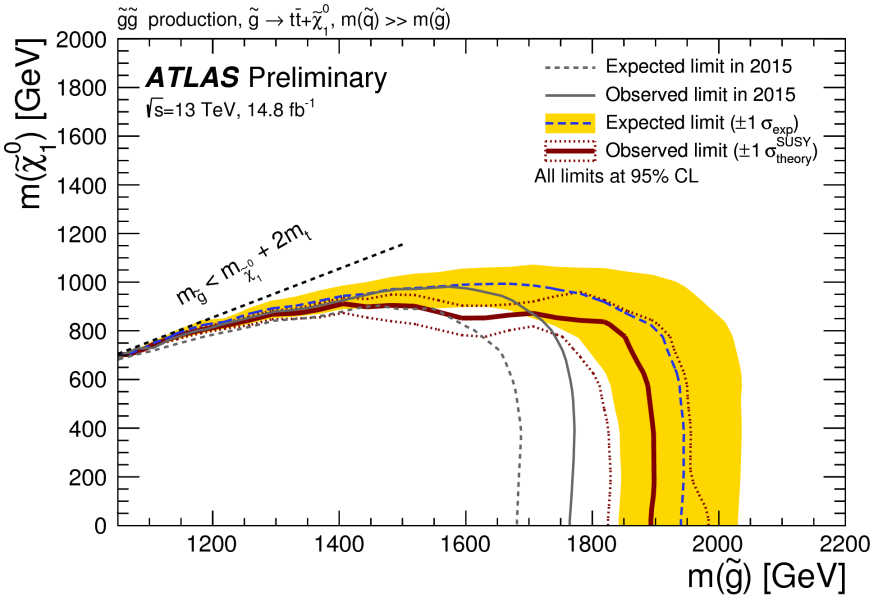


CMS summary



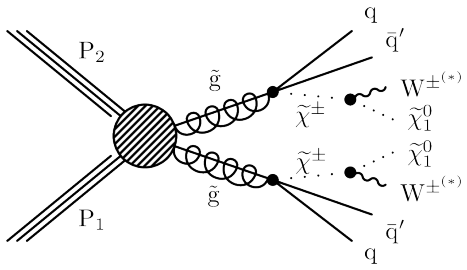
ATLAS multi-b

ATLAS-CONF-2016-052



Other results
- ATLAS-CONF-2016-037

Gluino production / chargino



Alternative decay chains in gluino production

- decays via a chargino and a $W^{(*)}$

Single lepton search

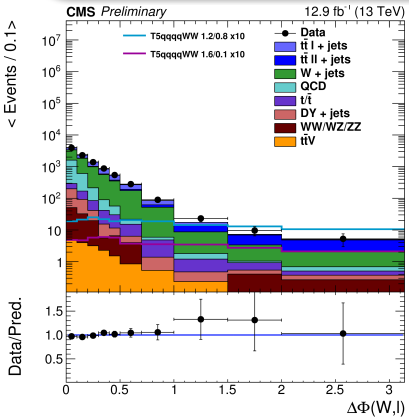
CMS-SUS-16-019

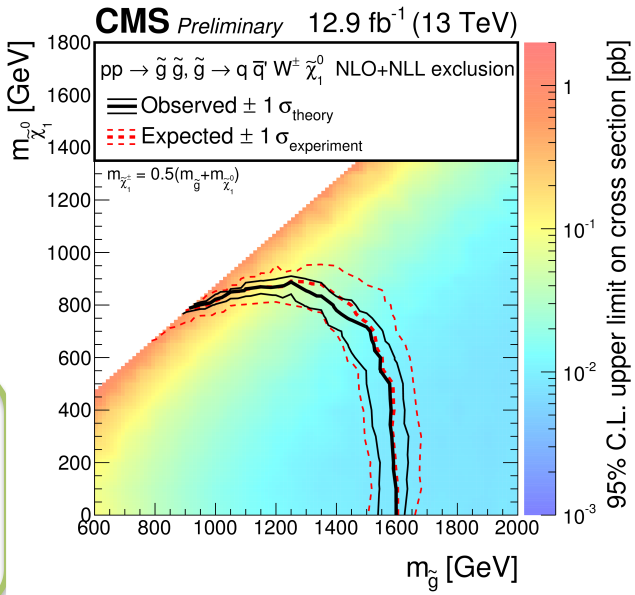
- 1 lepton, jets, (here no) b-jets
- key variables: H_T, MET, "W" p_T, and $\Delta\phi$("W",lepton)

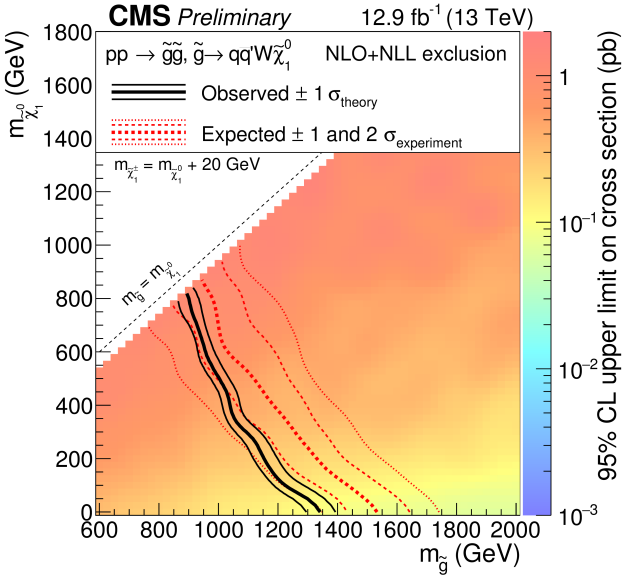
Same-sign dileptons

CMS-SUS-16-020

- small SM backgrounds (multi-boson, fake leptons, charge flip)
- binned in p_T(l), m_T, MET, H_T, #jets





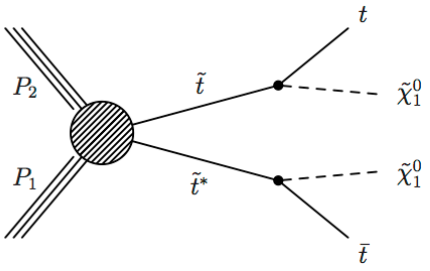


Other results

- ATLAS-CONF-2016-078
- ATLAS-CONF-2016-054
- CMS-SUS-16-014
- CMS-SUS-16-022

SQUARK PAIR PRODUCTION

Top squarks



Low-mass top squarks required for natural models

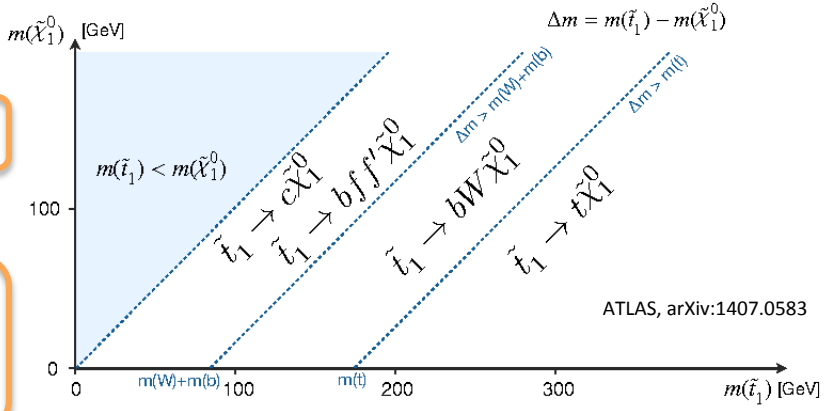
- could be the 2nd lightest SUSY particle (and the first detectable sparticle at the LHC)

Signature

- favored decay via $t^{(*)}$ and LSP: final states classified according to W decay mode
- approaches SM $t\bar{t}$ signature for $\Delta m \approx m(t)$ and low LSP mass

4-body decay

alternative: flavor-changing decays via charm

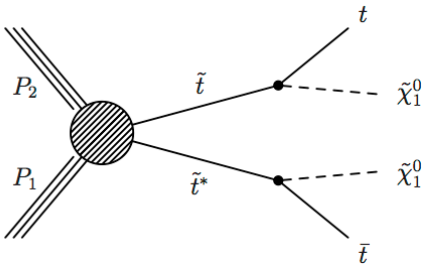


Decay via on-shell top quarks (2 body)

Decay via on-shell W (3 body)

if chargino is accessible: alternative decay to b-chargino

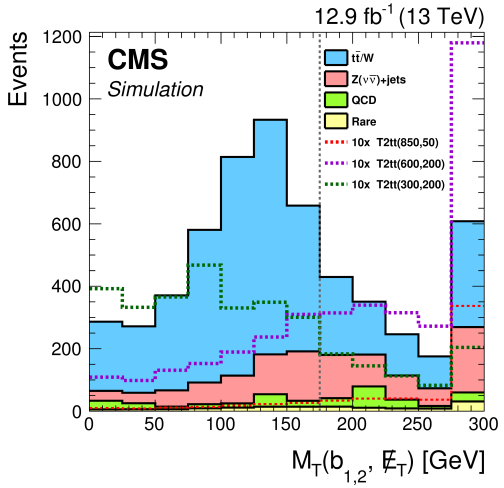
Top squarks

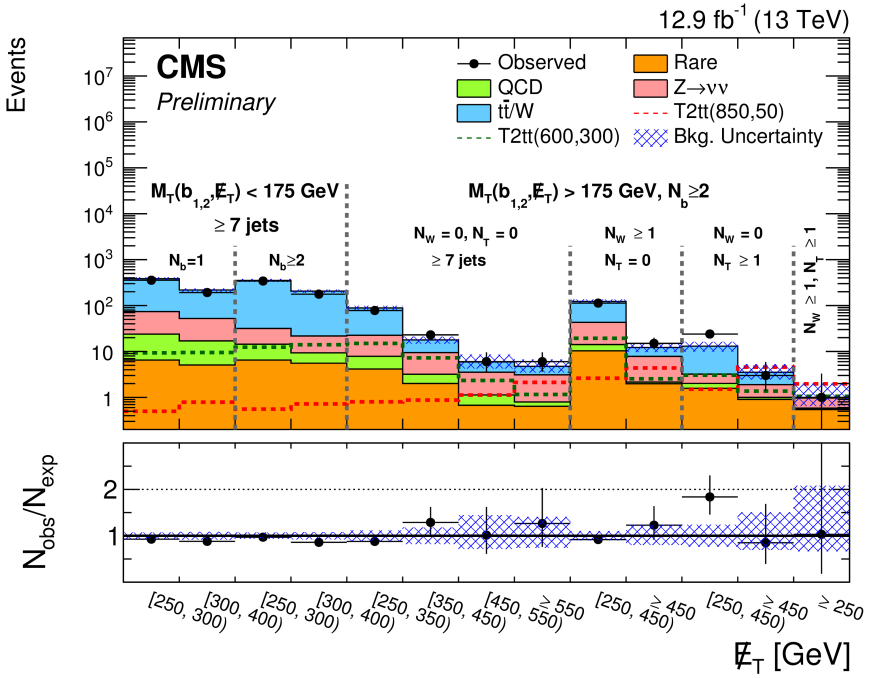


Hadronic search

CMS-SUS-2016-029

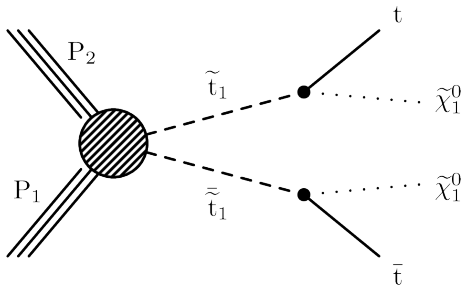
- optimizations for low and high Δm
  - high Δm: using #jets, #b-jets, $m_T(b)$, and MET; #tops and #Ws from jet substructure





Other results
ATLAS-CONF-2016-077
CMS-SUS-16-029
CMS-SUS-16-030
+ various inclusive searches

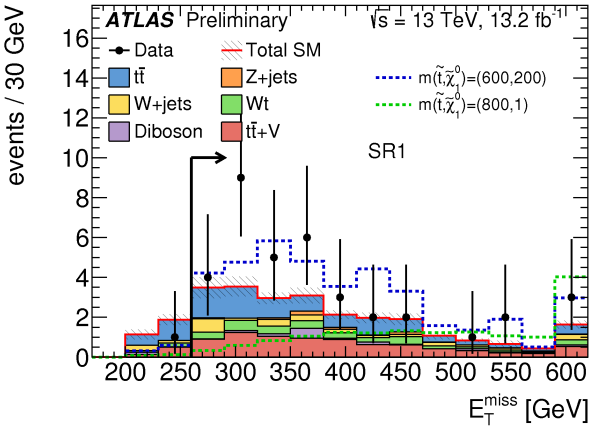
Top squarks

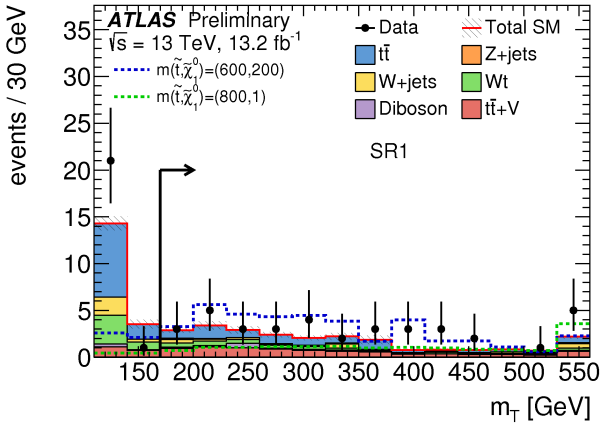


Single-lepton search

ATLAS-CONF-2016-050

- basic selection on jets, b-jets, MET
- signal regions optimized for different Δm and stop decays





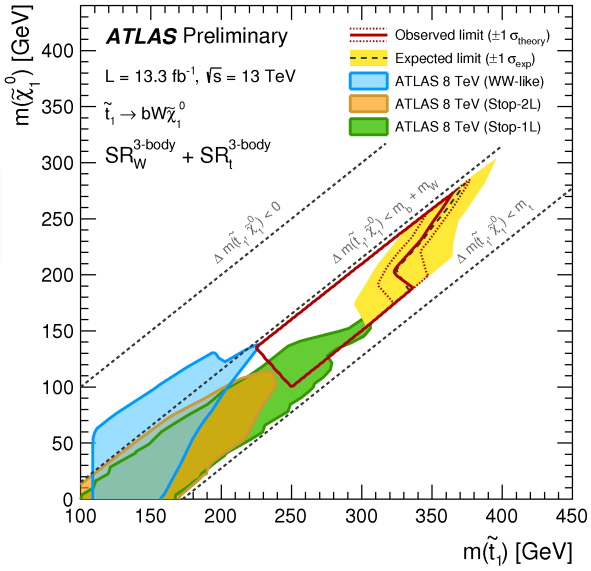
Distributions in one of the 1l signal regions

Dilepton search (ATLAS)

ATLAS-CONF-2016-076

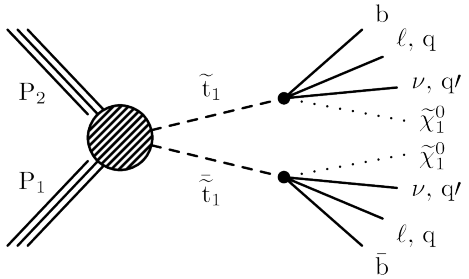
- basic selection on 2 OS leptons
- use of derived observables - super-razor, M_{T2}

exclusion for 3-body decays



Other results
CMS-SUS-16-029
CMS-SUS-16-030
+ various inclusive searches

Top squarks (the soft side)

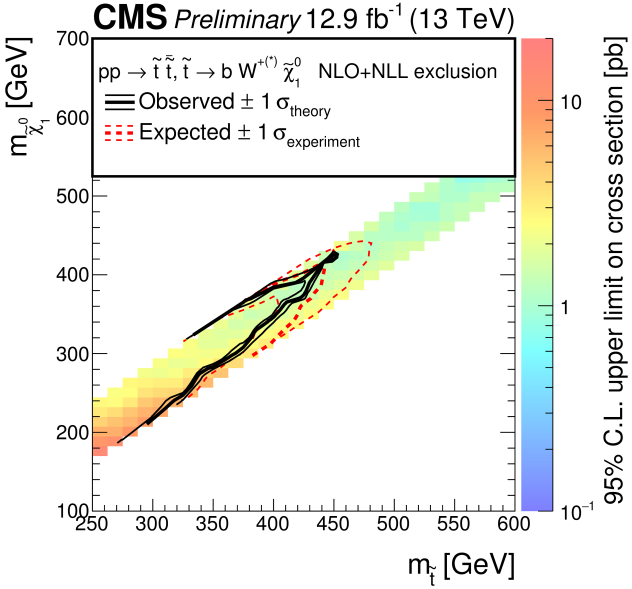


Direct production

- $\Delta m < m(W)$: experimentally challenging but could explain DM density due to co-annihilation
- handles: ISR jets, soft leptons

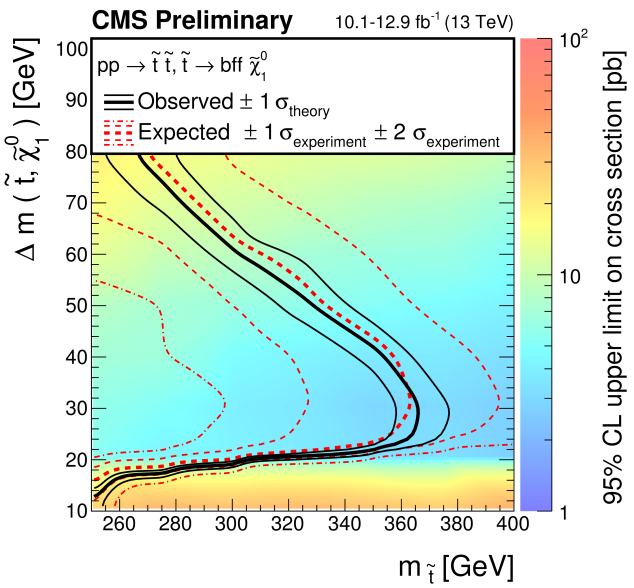
Hadronic

CMS-SUS-16-029



2 leptons

CMS-SUS-16-025



for prompt decays

Top squarks – alternatives

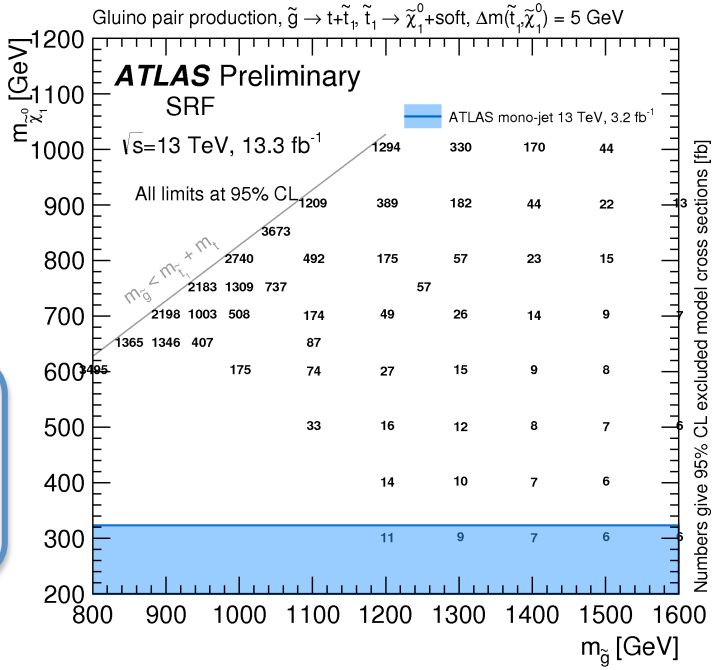
Lightest top squark might be undetectable in direct production

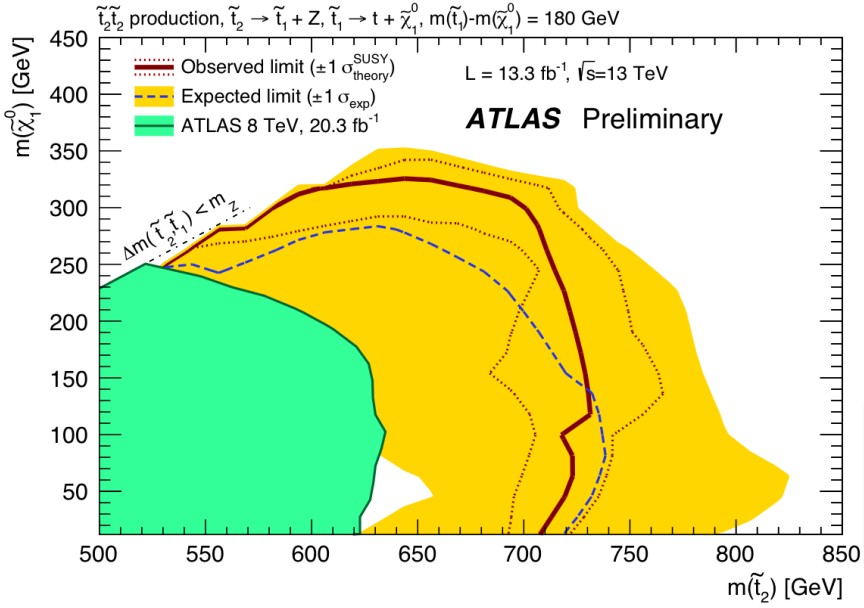
- search in decay chains!

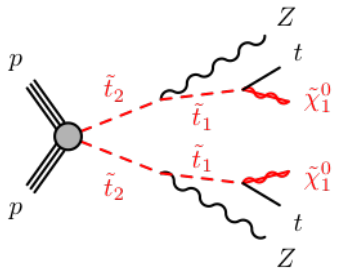
Hadronic search

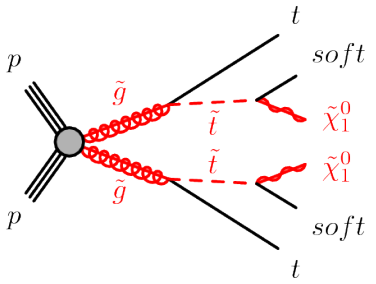
ATLAS-CONF-2016-077

- specific search region for highly boosted top quarks: uses mass of reclustered jets (R=1.2)







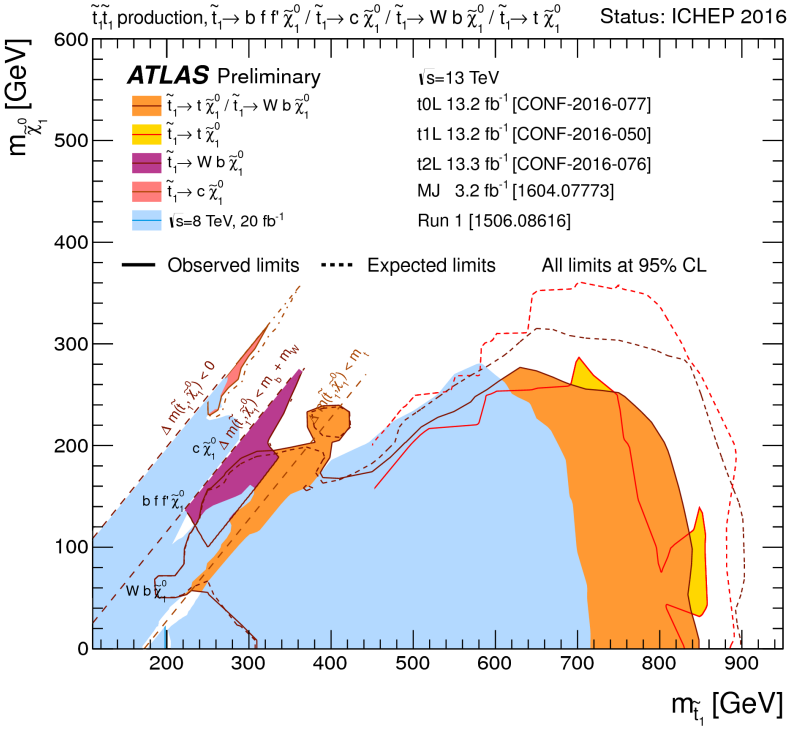


3-lepton + b search

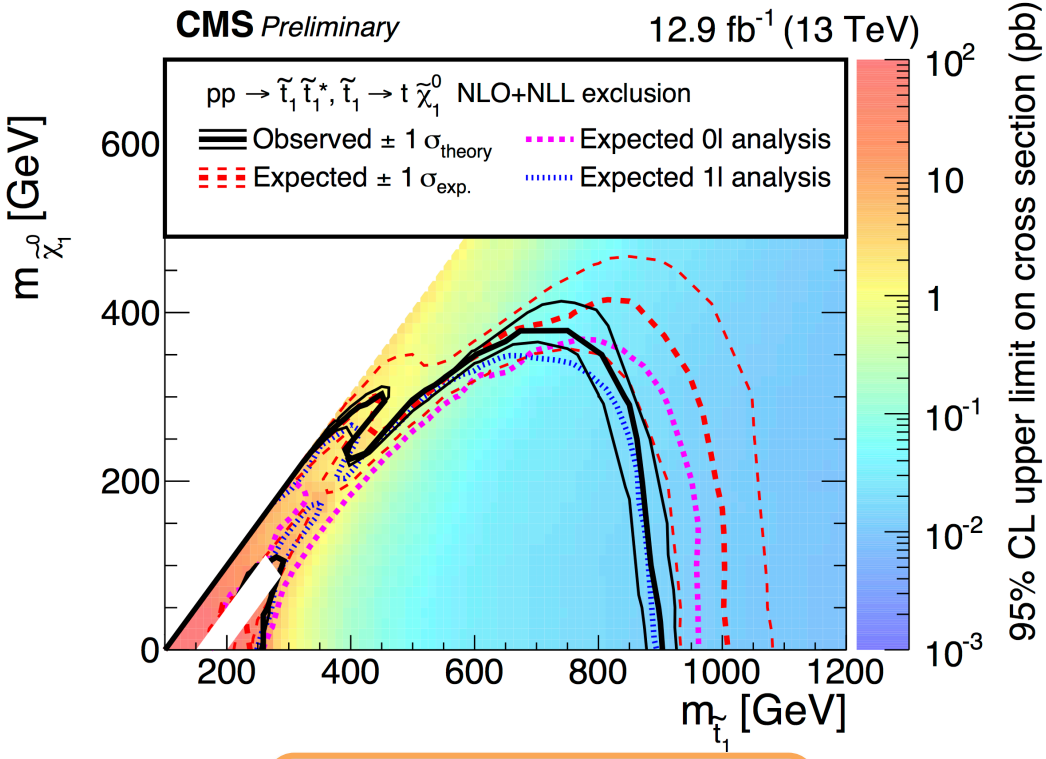
ATLAS-CONF-2016-038

- Z-decay + 3rd lepton
- other variables: #jets, #b, MET, p_T(Z)

Top squarks - summaries

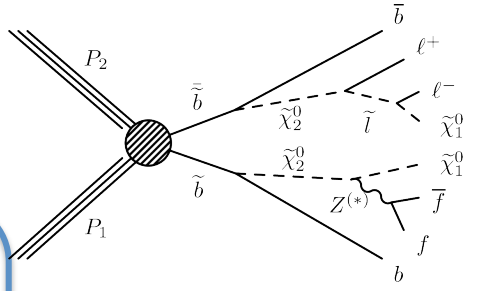


ATLAS summary



CMS 0l+1l combination for 2-/3-body decay

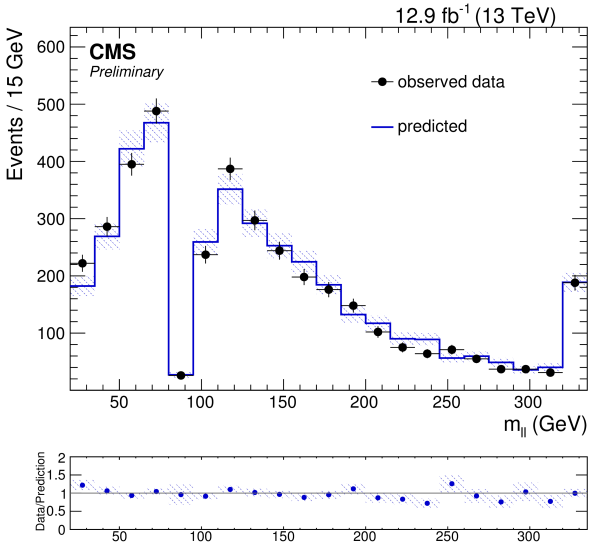
Dilepton mass edge



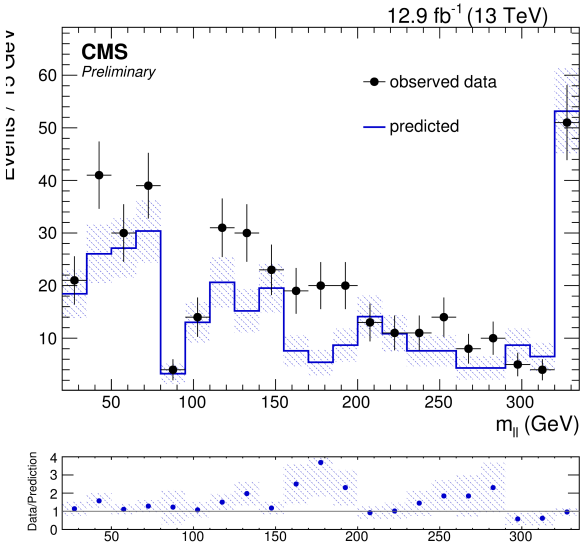
Opposite-sign dilepton search

CMS-SUS-16-021

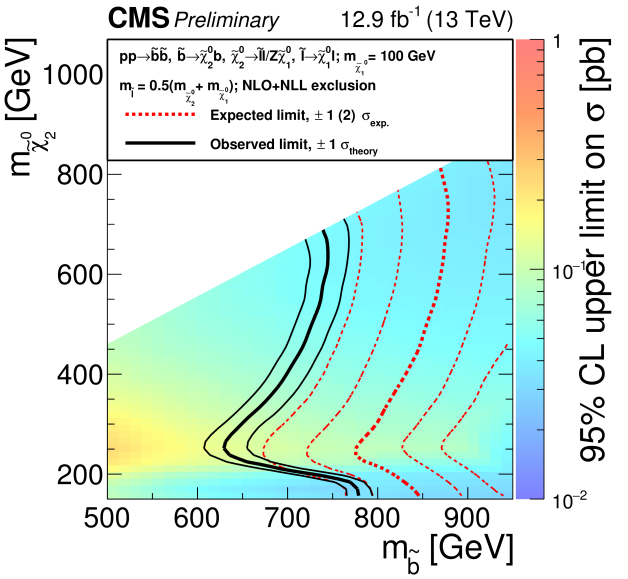
- Opposite-sign ee or μμ pair with jets and MET
- Here: off-Z regions targeting kinematic edge in decay chain
- dominant flavor-symmetric backgrounds estimated from data
- SRs binned acc. to tt discriminator, #jets, #b-jets, MET



tt-like

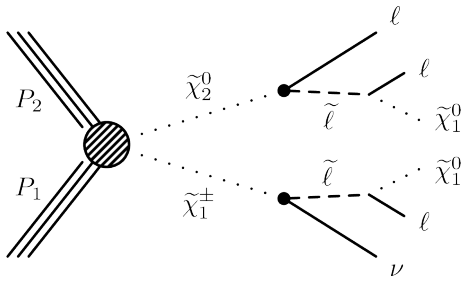


not tt-like



Electroweak Production Modes

Chargino / neutralino production



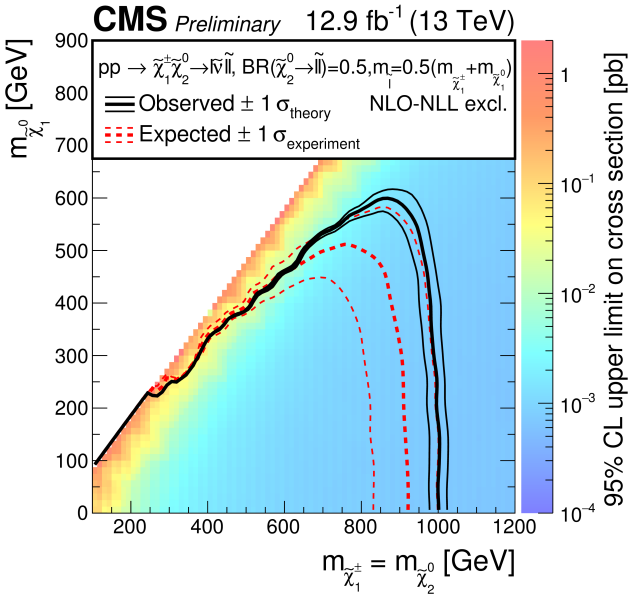
Direct production of "electroweakino" pairs

- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

Multilepton searches

CMS-SUS-16-024

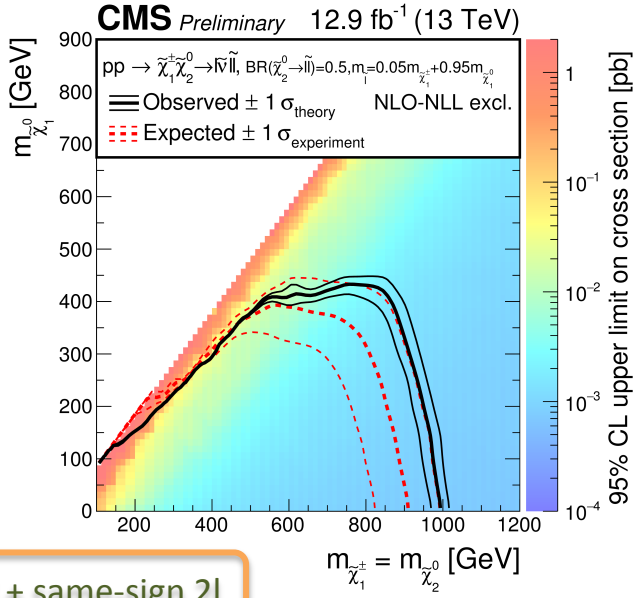
- 3 (or 4) leptons (includes combinations with 1 or 2 hadronically decaying τs)
- SRs binned in flavour&charge combination, MET, m(ll)/p_T(ll)



Effect of change in inter-mediate slepton mass

↔

Other results in EW prod.
CMS-SUS-16-021
CMS-SUS-16-025
CMS-SUS-16-026



3l + same-sign 2l

Chargino / neutralino production

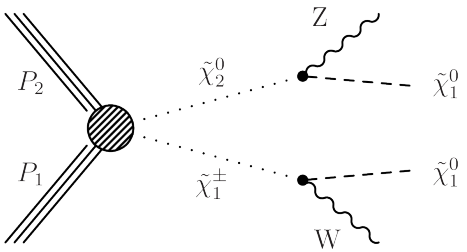
Strong motivation for small mass splittings in natural SUSY

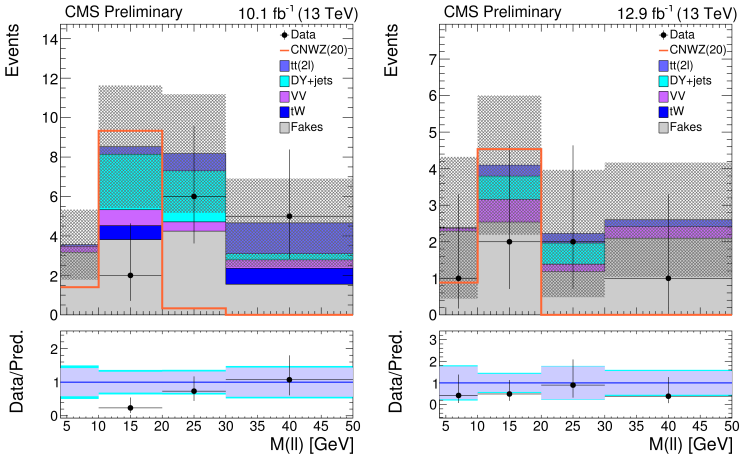
- $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ degenerate, $\tilde{\chi}_1^0$ only slightly lighter

Soft dilepton search

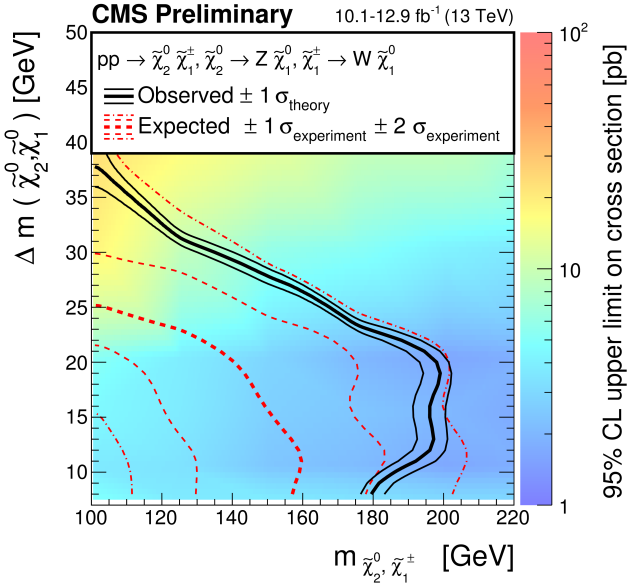
CMS-SUS-16-025

- need very low lepton p_Ts (≥3.5-5GeV)
  combination of pure MET & specific 2μ+MET triggers
- other selections: MET, H_T, b-jet veto



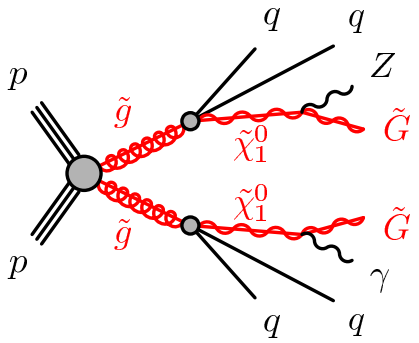


Dilepton mass spectrum
for low and high MET



GMSB SCENARIOS

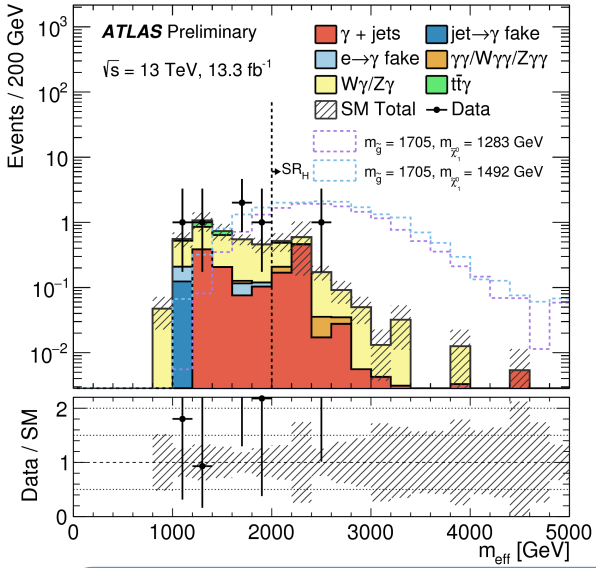
Gluino-induced Z/γ+gravitino

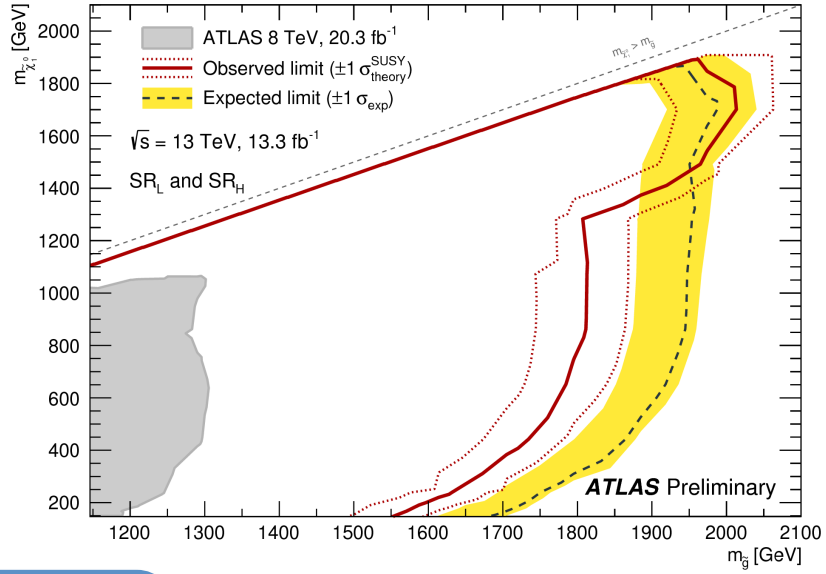


Photons + jets search

ATLAS-CONF-2016-066

- ≥1γ, jets, MET, 0 leptons
- key variables: #jets, m_{eff}, jet hierarchy
- 2 signal regions optimized for high and low gluino/NLSP splitting





Also:

ATLAS-CONF-2016-048

- specific search for t squark → τ slepton cascades

Other GMSB results.
CMS-SUS-16-021

R-PARITY VIOLATION

RPV in gluino or squark decays

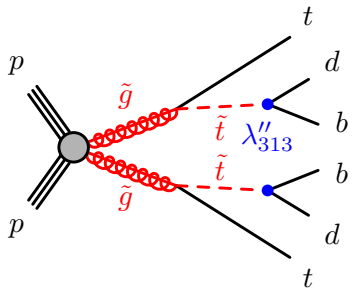
Decays proceed via B# violating couplings λ”

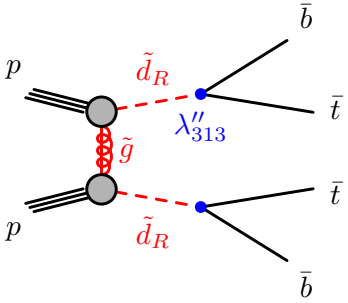
- Assume unchanged production, and prompt decays

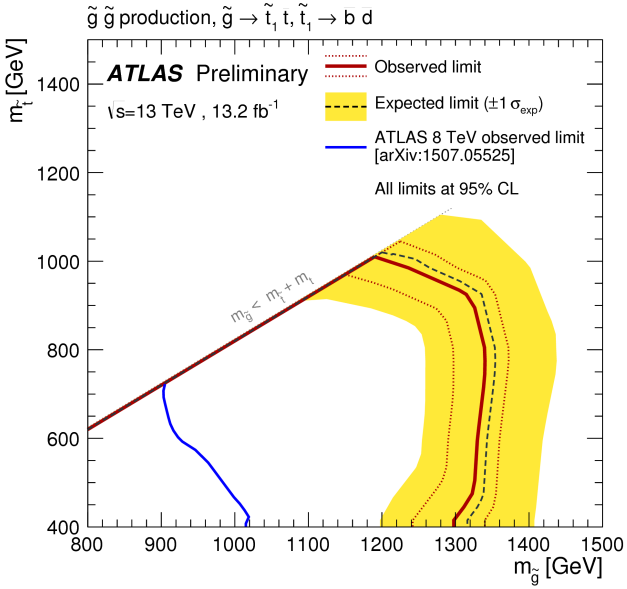
Same-sign dilepton / 3 lepton search

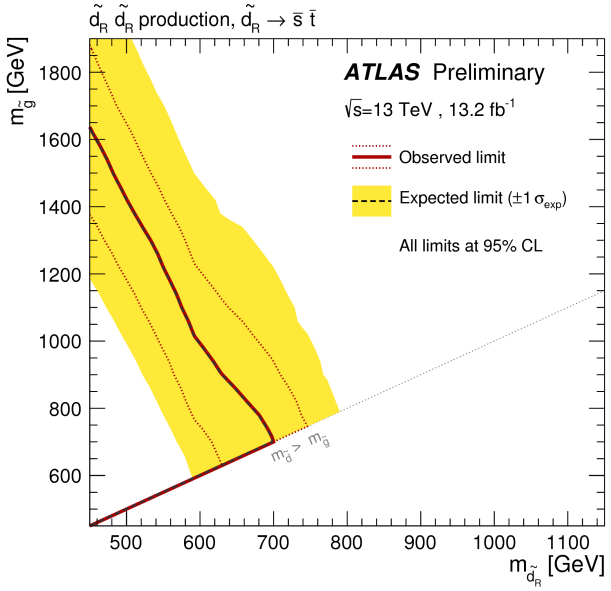
ATLAS-CONF-2016-037

- several signal regions sensitive to RPC and RPV models
- here: ≥2 leptons, ≥1 b-jet, ≥2 jets, m_{eff}, no MET requirement



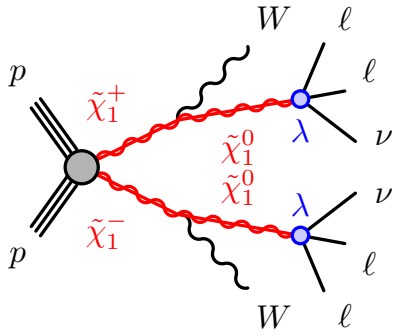






Other results
ATLAS-CONF-2016-084

RPV / EW production



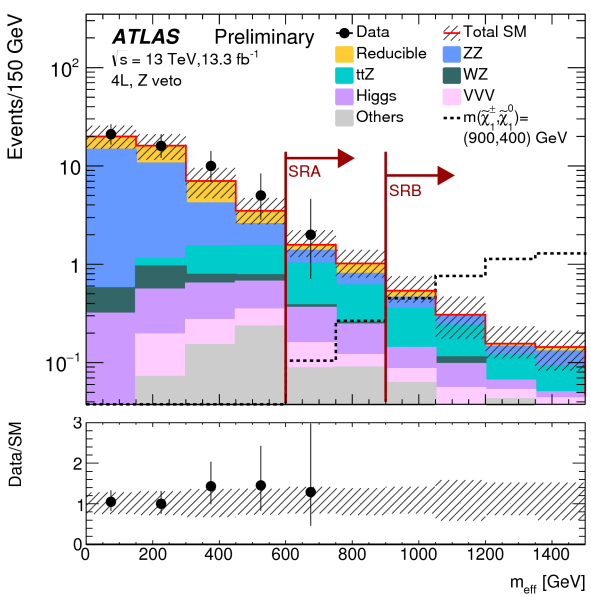
RPV in electroweak production

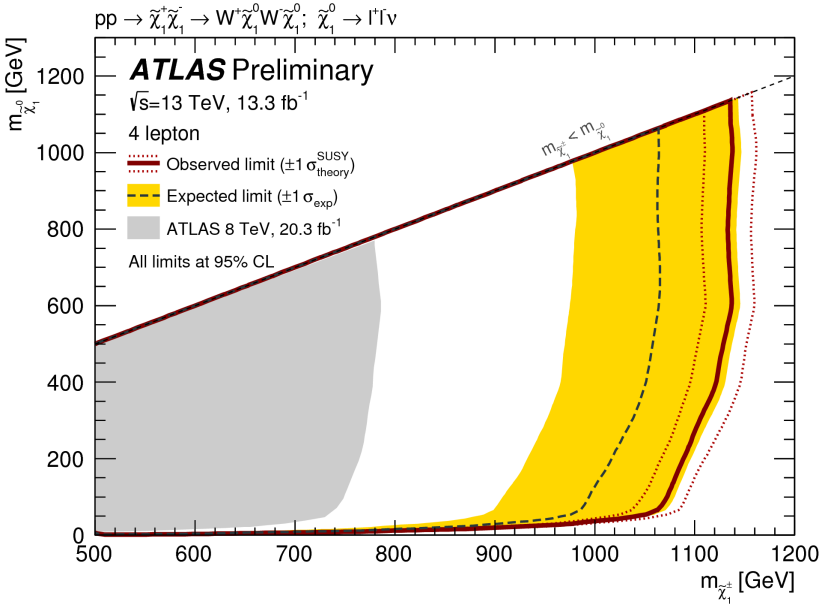
- decay via L#-violating coupling λ

Search in 4-lepton events

ATLAS-CONF-2016-075

- backgrounds from rare SM processes (ttX, multi-boson), fake leptons
- 2 signal regions with different m_{eff} requirements

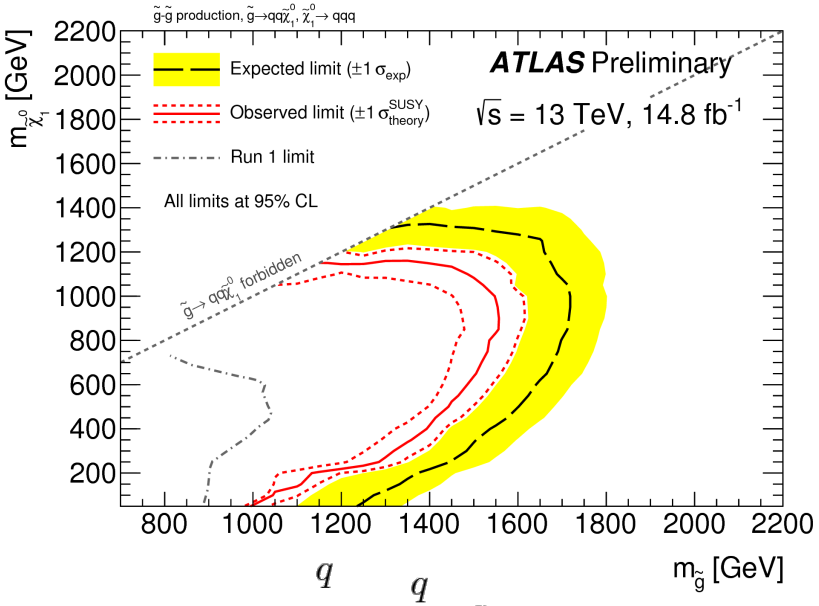


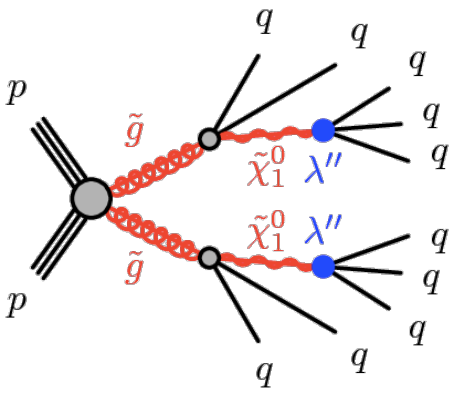


RPV in gluino production

RPV in gluino decays

- decay via B#-violating couplings λ”

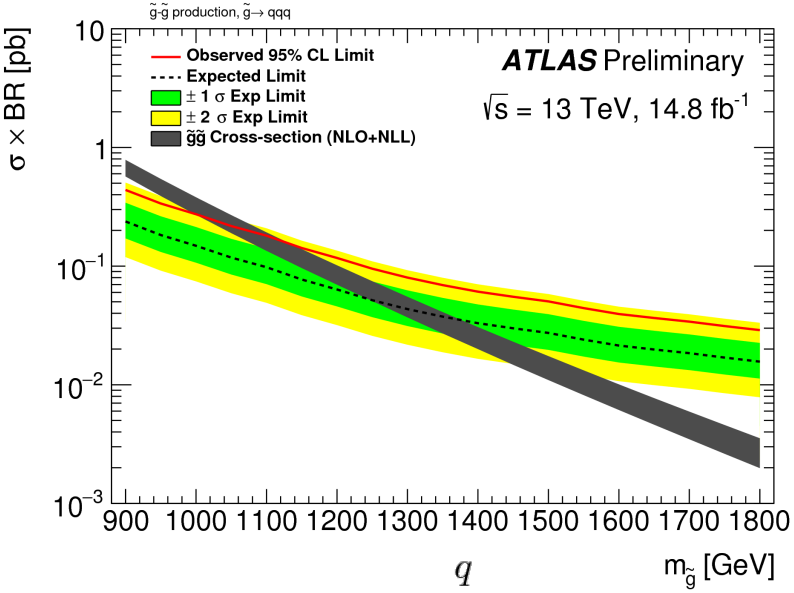


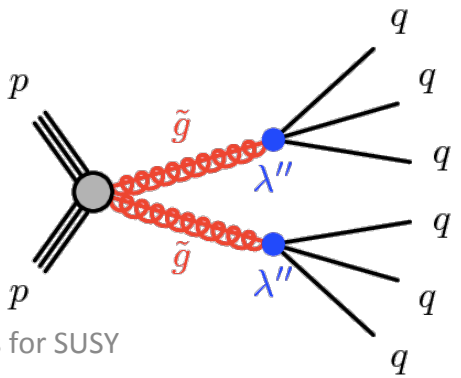


Multijet search

ATLAS-CONF-2016-057

- bkgs from rare SM processes, fake leptons
- 2 regions with different m_{eff} requirements





Competitive limit from CMS-SUS-16-013 (2015), but for exclusive decays to tbs!

SHORT LOOK BACK TO RUN1

Link with full models: pMSSM

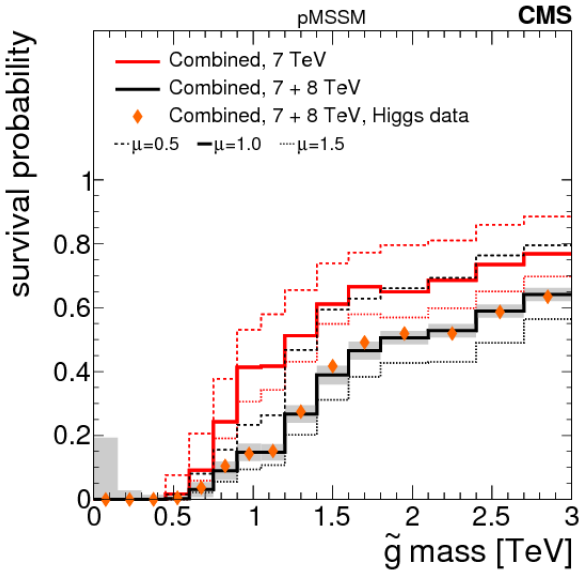
Phenomenological MSSM

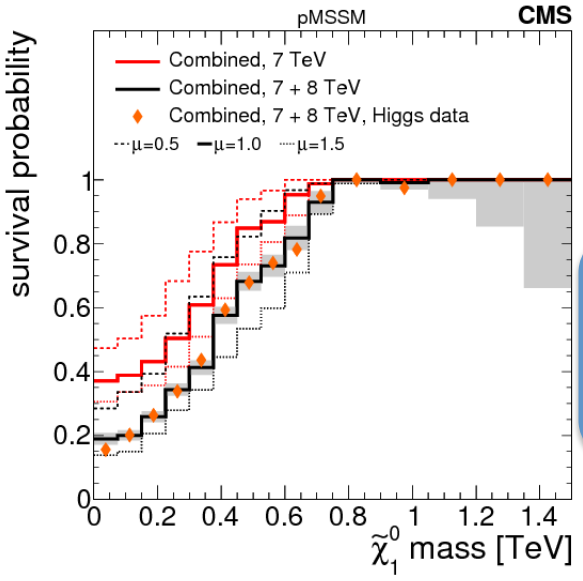
- catches essential MSSM features in 19-dim subspace
  - assumptions: no CPV couplings, R-parity conserving, degeneracy of 1st&2nd generation, MFV
- goal: understand impact on model parametes, limitations of SMS approach & "holes" in experimental MSSM coverage using scans of pMSSM parameter space

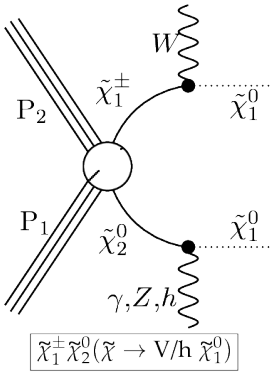
Impact of CMS searches

CMS, arXiv:1606.03577

- Bayesian analysis including 11 CMS analyses @ 7 and 8 TeV







dominant EW production → lower prob. to be excluded
unexcluded points typically at low visible and missing energy

Other exp. pMSSM study:
ATLAS, JHEP 10 (2015) 134

Link with full models: pMSSM DM study

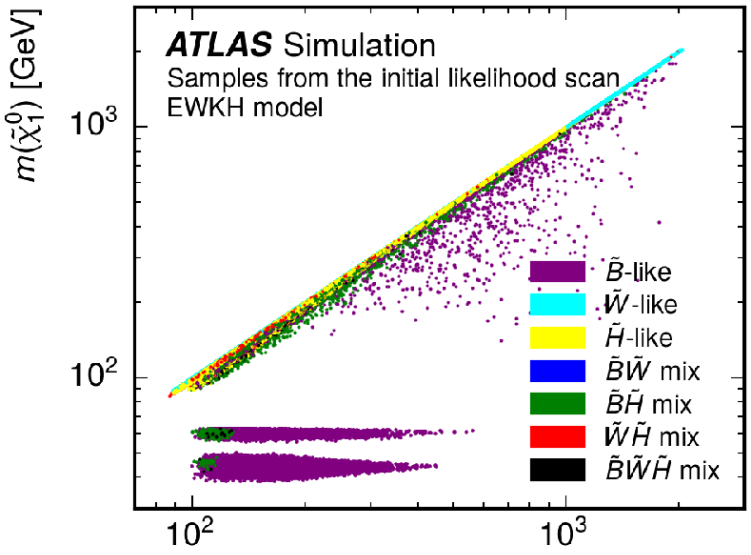
EWKH model

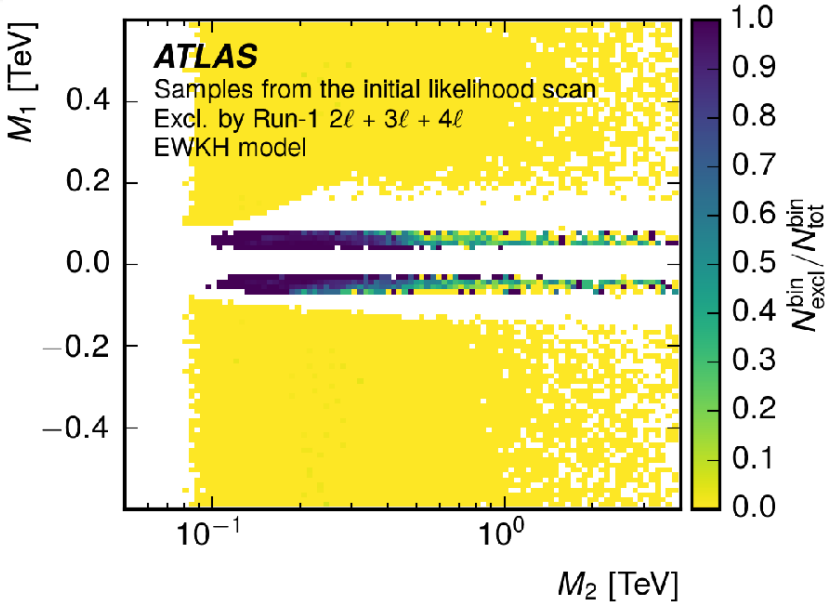
- pMSSM reduced to 5 parameters: M_1, M_2, μ, $\tan\beta$, m_A
  - quarks and sleptons are decoupled

Impact of ATLAS searches

ATLAS, arXiv:1608.00872

- 4 di- and multi-lepton analyses
- constraints from direct DM searches, relic density, flavor physics, …





direct impact on M_1, to a lesser extent M_2 & μ
highest exclusion rates at $\Omega_\chi h^2 \sim 10^{-2}$-$10^{-1}$, low $\sigma^{SI}_{\chi N}$

Summary

- Excellent LHC performance allowed for considerable increase in sensitivity with partial 2016 data set
  - Experiments performed a large set of analyses almost synchronously with data taking
- Searches now extended to more challenging scenarios
  - Electroweak production, compressed mass spectra, …
  - Can expect many more after end of 2016 data taking!
- Mass limits (in simplified model spectra!)
  - pushed to about 1.9 TeV (gluinos) and 900 GeV (top squarks); limits on EW production even for small mass differences

Much larger data sets will be available at the end of 2016 and during the rest of Run2, and we are looking forward to seeing first significant deviations from SM predictions!

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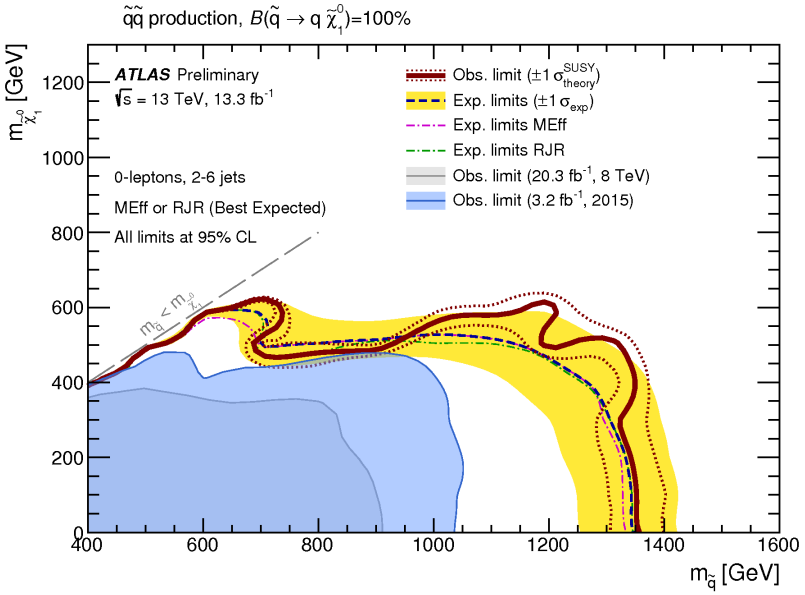
Additional Material

Light & b squark production

Hadronic analysis / strong production

- low #jets SRs targeting direct production

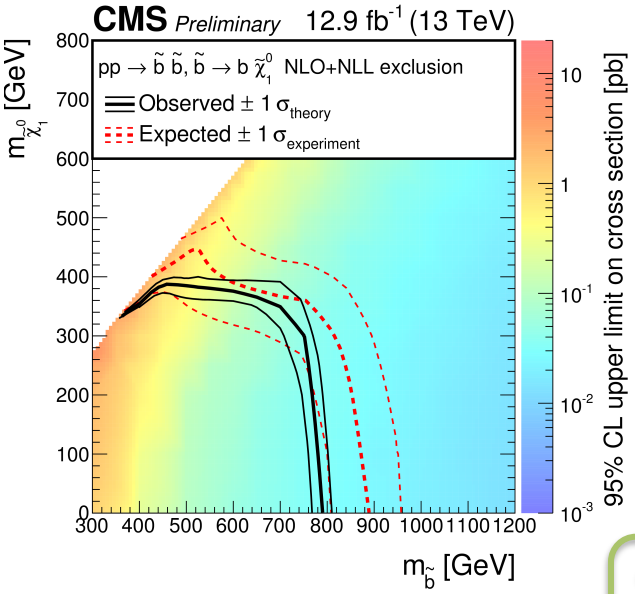
ATLAS-CONF-SUSY-2016-078



Inclusive hadronic analysis

- multijet rejection: α_T
- SRs binned in #jets, #b jets, H_T

CMS-SUS-16-016



Other results
CMS-SUS-16-014
CMS-SUS-16-015

Top squarks – alternative decays

Hadronic search

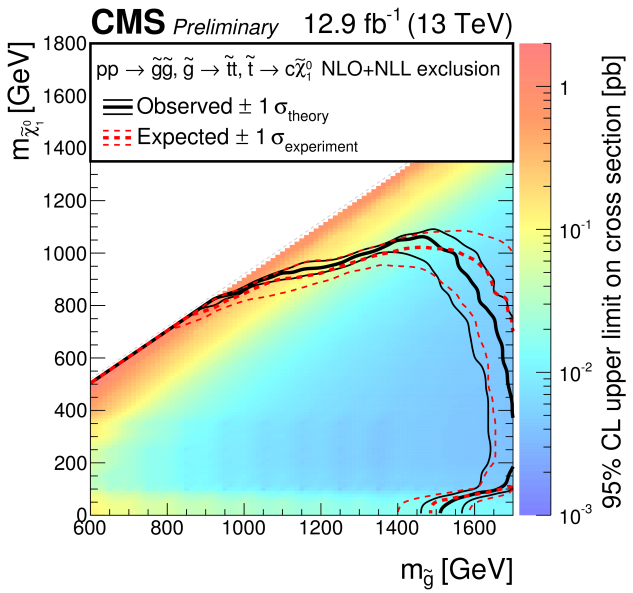
CMS-SUS-16-030

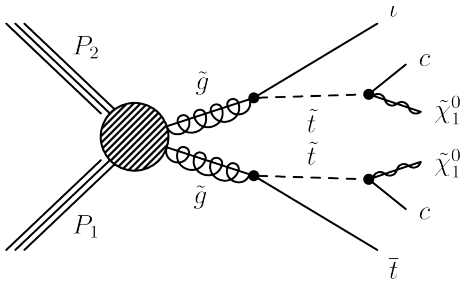
- Using top-tagger for wide p_T range (using 1-3 R=0.4 jets)

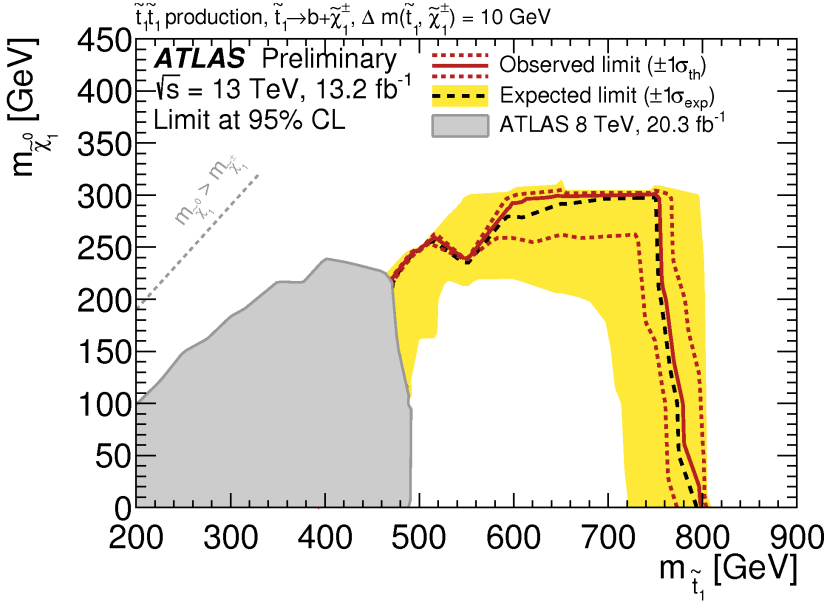
Decay via chargino

ATLAS-CONF-2016-050

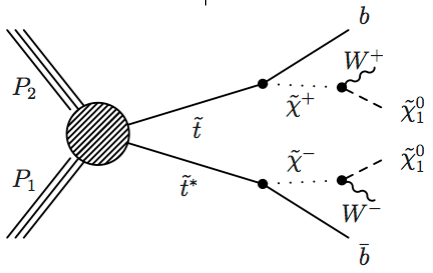
- interpretation exists for 0l, 1l, 2l channels here: single-lepton search



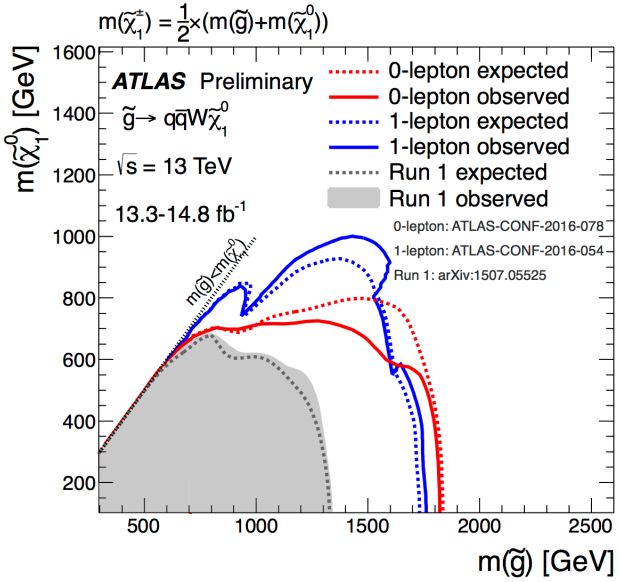


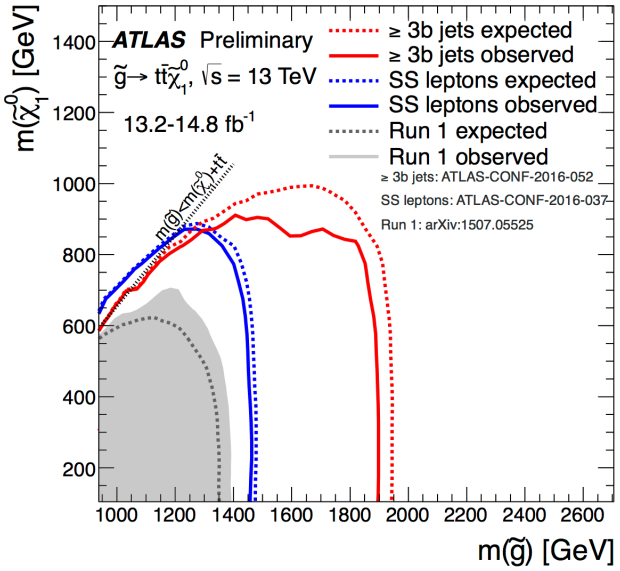


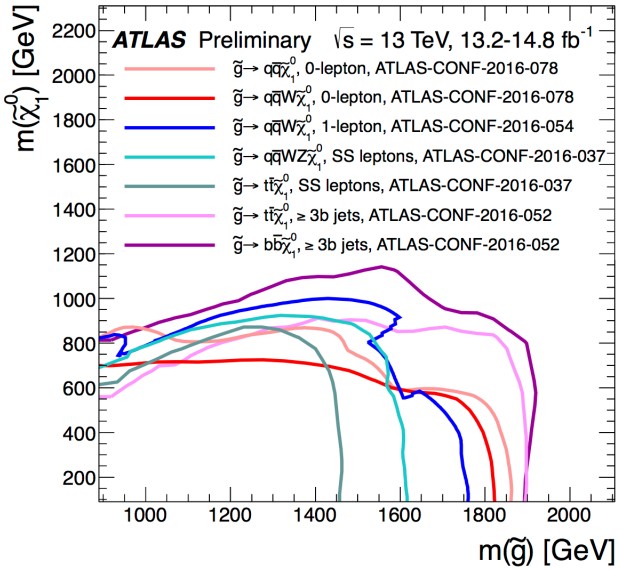
Other results
ATLAS-CONF-2016-077
ATLAS-CONF-2016-076
CMS-SUS-16-028
CMS-SUS-16-029



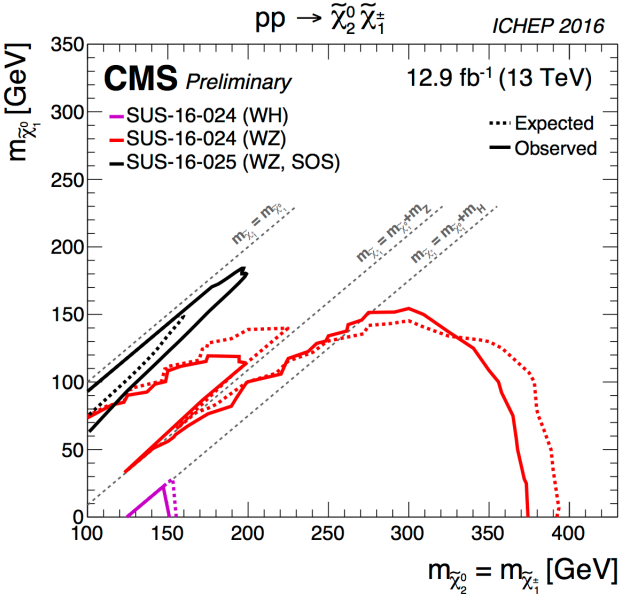
Summaries strong production (ATLAS)

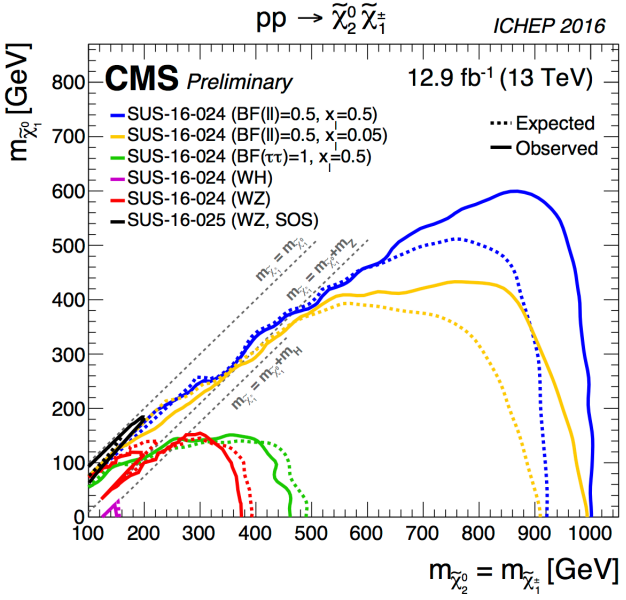




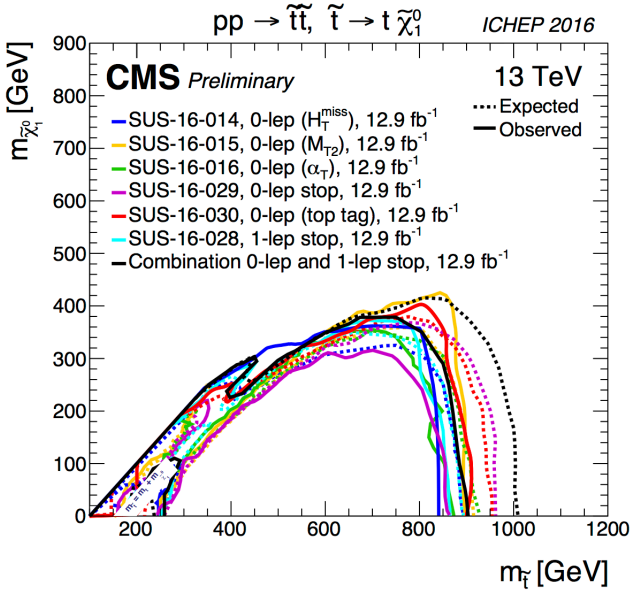


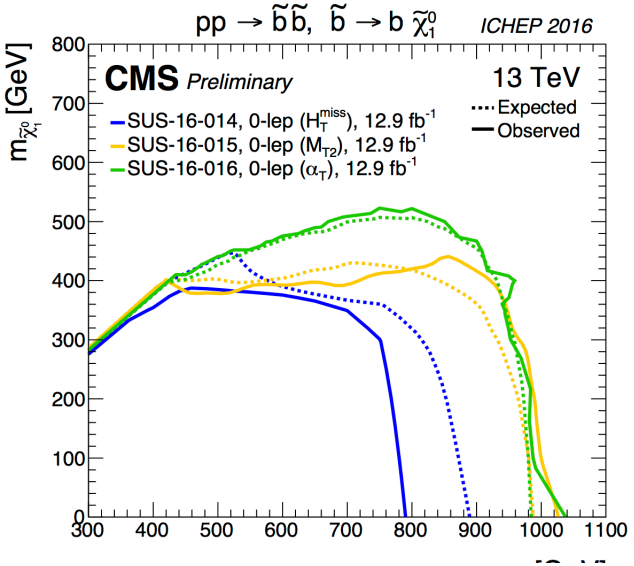
Summaries EW production (CMS)

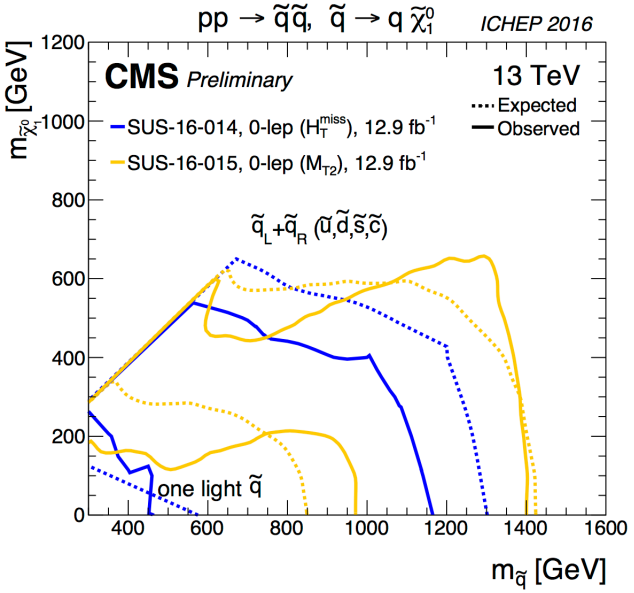




Summaries squark production (CMS)







Summaries gluino production (CMS)